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Published in:
Applied Physics Letters

DOI:
[10.1063/1.110356](https://doi.org/10.1063/1.110356)

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
1993

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Dierichs, M. M. T. M., Feenstra, B. J., Skalare, A., Honingh, C. E., Mees, J., van der Stadt, H., & de Graauw, T. (1993). Evaluation of niobium transmission lines up to the superconducting gap frequency. *Applied Physics Letters*, 63(2), 249-251. <https://doi.org/10.1063/1.110356>

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Citation: [Appl. Phys. Lett.](#) **63**, 249 (1993); doi: 10.1063/1.110356

View online: <https://doi.org/10.1063/1.110356>

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Evaluation of niobium transmission lines up to the superconducting gap frequency

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(Received 22 September 1992; accepted for publication 23 April 1993)

The frequency dependence of the coupling of niobium superconducting transmission lines is measured for frequencies up to and above the superconducting gap frequency. For this purpose superconducting microstrips are integrated in log-periodic planar antennas and the spectral response is measured by means of a Fourier transform spectrometer with $1\text{ }\mu\text{m}^2$ Nb/Al₂O₃/Nb SIS junctions as detectors. Resonances of microstrips are observed up to 650 GHz, the superconducting gap frequency of niobium, but above that frequency no resonances have been detected. The measured resonance frequencies are in good agreement with a dispersive model for superconducting transmission lines based on the Mattis-Bardeen theory. The radiation coupling is lower than calculated, indicating significant dielectric losses.

Superconducting transmission lines (stubs) are often used as an integrated tuning and matching network for superconducting tunnel junctions in mixers and detectors. In a waveguide mixer the geometrical capacitance of the junction can be additionally tuned by a backshort and an *E*-plane tuner. On a planar antenna, however, this capacitance can only be compensated by means of an integrated tuning network. The integrated tuning elements exist usually out of superconducting striplines. Until recently, dimensions of the structure are scaled down in size for higher frequencies, while very few results are published about the behavior of niobium above or close to the gap frequency.¹⁻³ Loss at this frequency can limit the use of transmission lines made out of niobium. In this paper we will compare calculated with measured resonances from a stub parallel to a junction and identify some problems which will arise at these high frequencies.

The first published measurements of integrated tuning elements used the self-pumped steps in *I-V* characteristics to measure the resonance of a stub.⁴ A more accurate and complete evaluation can be achieved with a Michelson interferometer used as a Fourier transform spectrometer (FTS).⁵ The source is a broad-band mercury arc lamp. In our case the usable frequency range is limited by a 50 μm thick kapton beam splitter and ranges from 150 to 1000 GHz. The spectral response of our device is derived from the current variation of the junction as a function of path-length difference of the Michelson. The Fourier transform of this interferogram yields the frequency response of the detector.

We use two junctions in series of each $1\text{ }\mu\text{m}^2$ area and a critical current density of 12000 A/cm² and we assume a specific capacitance of 55 fF/ μm^2 . The junctions are fabricated with the selective niobium over-etch process.

(SNOEP).⁷ The wiring layer on top of the junctions includes a stub for each junction. Both the antenna and the stub are made of niobium and are assumed to have a penetration depth of 100 nm.⁶ The dielectric layer between the ground plane (antenna) and the stub is 250 nm thick sputtered SiO₂. The devices are fabricated on a 200 μm thick fused quartz substrate.

A stub length of 500 μm and a width of 5 μm results in our case in a fundamental resonance around 100 GHz and harmonic resonances at multiple frequencies. The antenna is glued to a quartz lens and mounted in a liquid helium bath Dewar with only dc bias connections.

For an interpretation of the measured spectra we assume that the junction can be described at rf frequencies by the quantum impedance parallel to its geometrical capacitance. The quantum impedance is calculated using the equations from Tucker and Feldman⁸ assuming the experiment is working in the small signal limit. This means that we can neglect dependency on incident power. The characteristic impedance of the stub is calculated using the well-known equations for superconducting transmission lines.⁹ We include the loss (α) and dispersion (β) of niobium as a function of frequency in the calculation. Both parameters are calculated according to the paper of Kautz.¹ This is based on the theory of Mattis and Bardeen.¹⁰ The impedance of the stub follows from¹¹

$$Z = \frac{Z_0}{\tanh(\gamma \cdot l)}, \quad (1)$$

where Z_0 is the characteristic impedance of the transmission line, l is the length, and $\gamma = \alpha + i\beta$ is the propagation constant. In Eq. (1) we take into account the frequency dependency of Z_0 and γ . The coupling coefficient C_{rf} is defined as the fraction of the available power dissipated in the junction:

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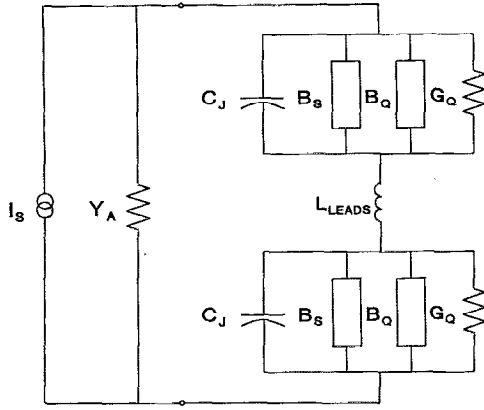


FIG. 1. Electrical equivalent of two junctions in series with integrated tuning elements.

$$C_{rf} = 1 - \left| \frac{Y_{ant} - Y_j^*}{Y_{ant} + Y_j} \right|^2, \quad (2)$$

where the impedance of the antenna is approximated by $Z_{ant} = 120 \Omega$,¹² $Y_{ant} = 1/Z_{ant}$, Y_j is the admittance of the junction with the stub in parallel, and * denotes the complex conjugate.

The electric equivalent of the structure is shown in Fig. 1. The radiation source is approximated by a current source I_s parallel to the antenna impedance. The leads inductance L_{leads} between the junctions can be neglected in the calculation. Each junction is represented by its geometrical capacitance C_J parallel to its quantum impedance ($G_Q + jB_Q$). The stub impedance is represented by B_S .

Because of the frequency dependency of the photon energy, the responsivity of the junction as a function of its I - V characteristic and frequency should also be taken into account. The junction responsivity R is determined by⁸

$$R = \frac{e}{\hbar\omega} \frac{I_{dc}(V_0 + \hbar\omega/e) - 2I_{dc}(V_0) + I_{dc}(V_0 - \hbar\omega/e)}{I_{dc}(V_0 + \hbar\omega/e) - I_{dc}(V_0 - \hbar\omega/e)}, \quad (3)$$

where ω is the frequency, e is the electron charge, and I_{dc} is the dc current of the junction at the bias voltage V_0 . Using Eqs. (2) and (3), the response of the detector to the incident radiation as a function of frequency and bias voltage can be calculated.

Figure 2 shows the coupling C_{rf} calculated for a device with a lossless stripline (dotted line) and one with a lossy stripline (dashed line), and the coupling measurement with the FTS (solid line). In the two calculated cases the responsivity and the quantum impedance of the junction are included because these effects are independent of the tuning network. The height of the calculated peaks is normalized to the second peak, because both the antenna and the FTS are not optimized for frequencies below 150 GHz. Notice the gradual reduction of peak height below the gap frequency (650 GHz). This effect is mainly caused by the junction responsivity. In Fig. 2 we also see some dispersion as can be expected from the theory of Mattis and Bardeen. Observable resonances are not predicted nor observed above the gap frequency, because the superconducting ma-

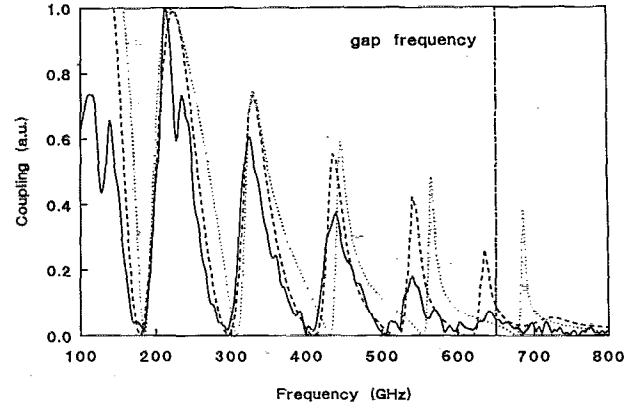


FIG. 2. Calculated intensities for a structure with a lossless stub (dotted line) compared to a structure with a lossy stub according to Mattis-Bardeen theory (dashed line) as a function of frequency. These results are compared with a measurement of a structure with a 500 μm long niobium stub. For reference the gap frequency of niobium (650 GHz) is indicated by a dash-dotted line.

terial starts behaving like a normal metal. We also see that the resonance at 200 GHz consists of two peaks. This is probably caused by coupling of one stripline to the opposite junction. The used bias voltage is $V_0 = 4.8$ mV, with the gap voltage at $V_g = 5.2$ mV.

A comparison between the calculations and the measurements for niobium shows a fairly good agreement above 200 GHz. Apparently the dispersion is very well predicted by the theory but the coupling shows more loss than we calculated. This may be caused by losses in the dielectric, because the absorption of fused quartz is fairly high for frequencies of about 1 up to around 100 THz.¹³ Obviously, sputtered quartz has more losses and this can explain the extra loss in coupling. The extra loss cannot be explained by the antenna coupling, because it has a flat response from 150 to around 800 GHz.

For improved coupling above the gap frequency both the niobium electrodes as well as the SiO_2 dielectric should be replaced by different materials. Niobium can be replaced by NbN or by a normal metal, e.g., gold, because they have less loss at these frequencies. For the dielectric, separate measurements should be performed for carefully determining its properties.

In conclusion, the resonances of niobium stubs with Nb/ Al_2O_3 /Nb junctions are measured and modeled. We can explain the observed frequency dependency of the coupling by taking into account the junction quantum impedance, its responsivity, and the loss and dispersion of niobium as known from the Mattis-Bardeen theory. We do observe more loss than calculated, which may be caused by dielectric losses in the sputtered SiO_2 layer. In the measurements we do not observe clear resonances above the gap frequency of niobium (650 GHz). This is in agreement with our model calculations.

We thank T. M. Klapwijk for reading the manuscript, H. G. Golstein, J. J. Wijnbergen, and G. de Groot for their help with the Michelson interferometer, H. H. A. Schaeffer for the mechanical support, and R. A. Panhuyzen and G. de Lange for stimulating discussions. This work was sup-

ported by the Stichting Technische Wetenschappen (STW) and the Stichting voor Fundamenteel Onderzoek der Materie (FOM), which are part of the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO). We also acknowledge the financial support of the European Space Agency (ESA) through Contract 7898/88/NL/PB(SC).

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